A model-based approach to control over packet-switching networks, with application to Industrial Ethernet

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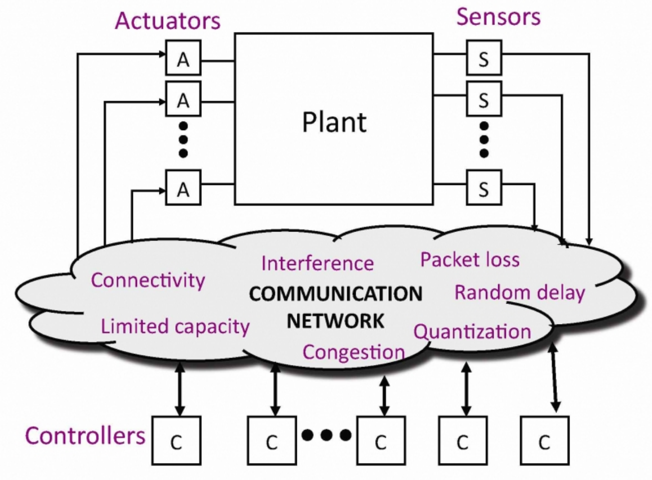
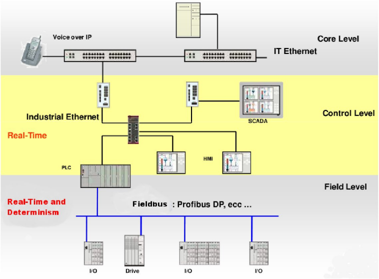
Networked Control Systems: structure and inherent problems



The classical architecture and the new trend in automation



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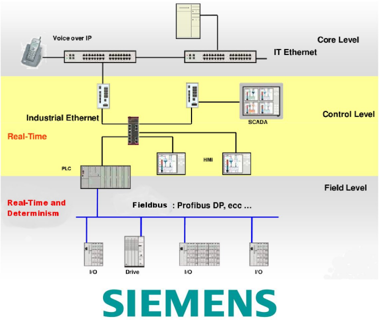

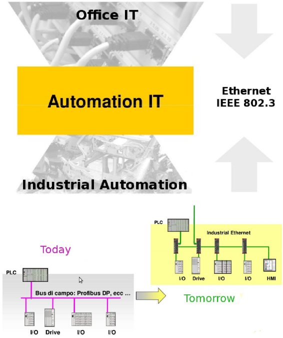

Uniform architecture: advantages and drawbacks

Advantages:

- transmission speed increased up to 1 Gbit/s
- increased ability of wiring long distances
- the possibility to use an uniform structure
- the ability to connect several hundreds of nodes

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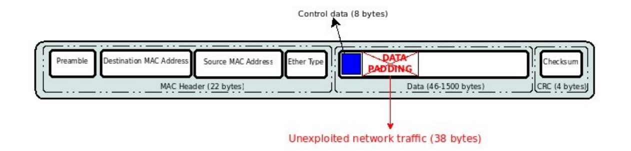
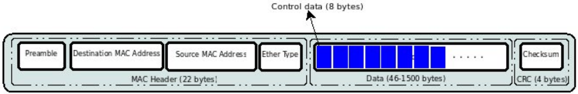
Drawbacks:



Goals of this work



Goals:

- lowering the packet rate
- exploiting the bandwidth ensuring a certain quality of performace of the control
- tolerate larger network delays

General assumptions:

1) the trasmission is time-periodic
2) no packet dropout occurr
3) the acquisition of all packets measurements, w.r.t. a given sending time, is guaranteed
4) the quantization effect can be neglected
5) sensors and actuators are time-driven, while the controller is event-driven
6) the overall state of the plant is sensorized

Definition 1:

- the sending time of the sensors is defined as an increasing sequence: $\boldsymbol{\tau} = \{\tau_i\} : \tau_i > 0, \forall i \in \mathbb{N}$

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Mathematical definitions

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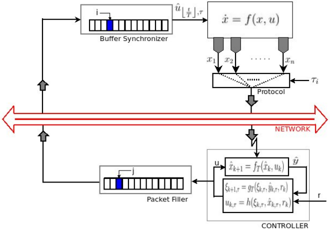
Definition 3:

- the Maximum Allowable Time Interval (MATI) on the sensors side, between two consecutive successfull accesses to the network, is defined as: $\exists \sigma : 0 < (\tau_{i+1} - \tau_i) \leq \sigma \, \forall i \in \mathbb{N}$

The Packet-Based Control (PBC) approach



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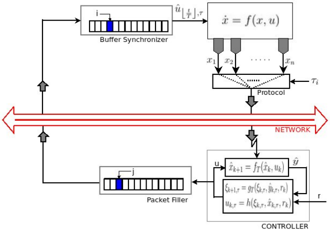

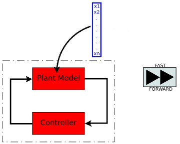

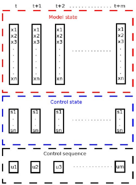

Packet filler and the Horizon H:

1. the packet will be filled by the controller as:

$$u_{k,\tau} = h(\xi_{k,\tau}, \hat{x}_{k,\tau}, r_k) : \tau = \max_{i \in \mathbb{N}} \left\{ \tau_i \in \boldsymbol{\tau} : \tau_i + \delta_i \leq \left\lfloor \frac{t}{T} \right\rfloor T \right\}, k = \frac{\tau}{T}, \frac{\tau+1}{T}, \ldots, \frac{\tau+H}{T}$$

2. in order for the plant not to remain without an available control, we must assure the following condition to hold:

$$(\tau_{i+1} + \delta_{i+1}) - \tau_i < H, \forall i \in \mathbb{N}$$

Effectiveness of the control approach:

This analysis is aimed at providing insights on the merits of the proposed strategy in terms of bandwidth economy and real-time hardness for the communication link respect to a classical control approach. The analysis will focus on the meaning and the effects of the choice of various parameters such as the **horizon of prediction (h)**, **the time interval between two consecutive successfull accesses to the network (σ)** (MATI), and **the computational power (k^{cmp})**.

Mathematical characterization of a frame:

$$B = B_f + hB_c$$

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The overall delay:

$$\delta = \delta^{net} + k^{cmp} h$$

Mathematical analysis

Horizon of control:

- $h \geq \sigma + \delta$

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Comparison between the classical control approach and PBC:

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- $B_f + B_c \geq \frac{B_f+hB_c}{h-\delta}$
- $h \geq \frac{\frac{B_f}{B_c}(1+\delta^{net})+\delta^{net}}{\frac{B_f}{B_c}(1-k^{cmp})-k^{cmp}} \rightarrow h = \left\lceil \frac{\sigma+\delta^{net}}{1-k^{cmp}} \right\rceil \geq \frac{\frac{B_f}{B_c}(1+\delta^{net})+\delta^{net}}{\frac{B_f}{B_c}(1-k^{cmp})-k^{cmp}}$

Mathematical analisys

A set of sufficient conditions that ensure the satisfaction of inequalities is given by:

$$\begin{cases} k^{cmp} & \leq & 1 - \frac{B_c}{B_f} \\ \sigma & \geq & \frac{B_f}{B_c}(\delta^{net} + 1) \end{cases}$$

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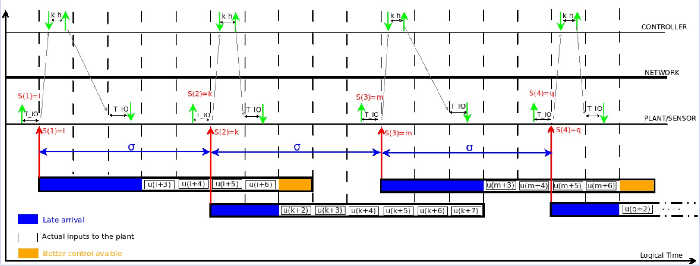
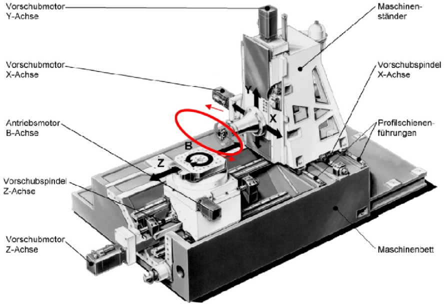
The formulation expresses bounds for the minimum computational speed and the maximum time incurring between two consecutive sensor readings, both expressed as function of the network parameters (namely the cost of the fixed data contained in each packet, the cost of a single control value and the upper bound for the network delay). The following figure shows how the packets are used considering an horizon $h = 8$ and delay $\delta = 3$.



Benchmark “Cutting a Circle”

The aim of this case study is to control a machine tool. “Cutting a circle” is a meaningful benchmark both for general CNC machines and especially for machines controlled over a network.

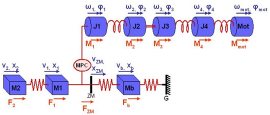


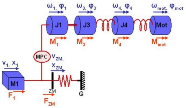
The machine tool (CNC)

The cutting must be performed by controlling linear motion of two axes (*X* and *Z*). They are orthogonal to each other.

The *X* axis consists of three functional parts: **the driven train**, **the sledge**, and **the machine bed**, coupled by a conversion element that allows translation between rotatory and translational movement.

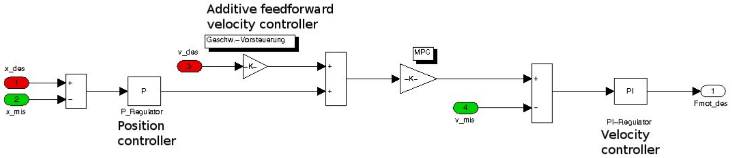
Since the Z axis is mounted on the X axis, its model is composed by **the sledge** and **the bed**:





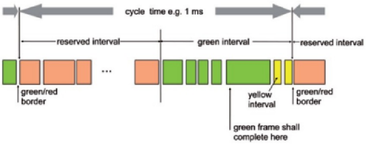
The controller for the motion control:

The controllers of the two axes are decoupled. The control over network can cause different delays for the motion of the axes introducing a phase offset that distorts the resulting trajectory from a circular to an elliptic shape. The feedback controller of each axis is realized as a cascade controller.



The network: PROFINET

The main characteristic of PROFINET is the capability to distinguish different traffic classes. The standard is based on a Time-Division Multiplexing (TDM) scheme, it allows to apply different Quality of Service (QoS) strategies for the traffic classes. Time is subdivided into a fixed communication cycle that is repeated over and over again.



Traffic classes

- IRT class: each communication cycle starts with "*red-phase*". In this class the synchronization is necessary
- non-real time class: the "*green-phase*" is dedicated for the communication non-real-time
- transistion phase: it is the "*yellow-phase*"at the end of the green interval. In this interval, the frames are only sent out if they are short enough so that their trasmission ends before the start of the next cycle

Benchmarks:

The ISO 25.040.20 specifies methods of testing and evaluating the circular deviation during the motion along the circular path, produced by the simultaneous movements of two axes. For the problem in hand, Siemens has choosen and used three relevant benchmarks.

- **Average radial relative error:** deviation of the average radius of the generated trajectory from the desired radius:

$$e_A = \frac{r_d - r_a}{r_d}$$

- **Maximum radial relative error:** maximal absolute deviation from the average radius calculated:

$$e_S = \max_{t \in [0,T]} \frac{r(t) - r_a}{r_d}$$

- **Area error:** represents the average distance of the tool from its desired position during the motion:

$$e_T = \frac{1}{r_d T} \int_0^T |\vec{x}_d(t) - \vec{x}(t)| \, dt$$

where $\vec{x}_d(t)$ is the desired trajectory defined over time, $\vec{x}(t)$ the contour realized by the machine tool, and r_d, r_a are respectively the desired radius and the average radius.

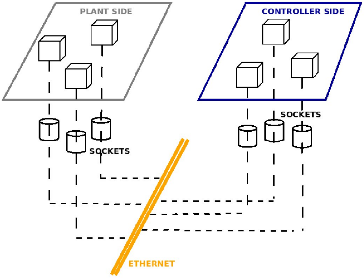
The main parameters and :

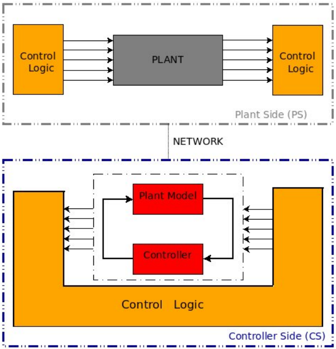
All relevant parameters for a simulation application control are listed in the tables, as provided by Siemens.

Parameter	Meaning of parameter	Value
R	Setpoint radius of circle	$5cm$
V	Cutting speed	$6m/min$
jitter on sampling of the sensor	jitter	$1\mu s$

	Network parameters
Trasmission bit rate	100 Mbit/s
Network delay	$3\mu s$
"Time Data Cycle" T_DC	$125\mu s$
Jitter of delay	$0.5\mu s$

A simulator for the Packet-Based Control approach





Simulation results:

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Introduction

Motivations

Problem formulation

The Packet-Based Control (PBC)

Mathematical analysis

Case study

Simulator "CoNCS"

Results

Contribution and conclusions:

Future works

Index loss in performance:

For evaluating the loss in performance due to the control over network, we have fixed, for the three benchmarks, an index comparing between the control without network ($b_{nominal}$) and the same performance indicators with network (b_{net}):

$$I = \frac{b_{net} - b_{nominal}}{b_{nominal}}.$$

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Siemens performance loss:

	area error	average radial rel. error	maximum radial rel. error
Conventional control	1.1634	1.2868	0.0858

Simulation results

PBC approach:

We assume to represent each control value on 8 bytes, since Ethernet have a fixed overhead of 26 bytes for each packet (we do not consider data padding), then $\frac{B_f}{B_c} = 3.25$. If we use $k^{cmp} = 0.5$ and consider $\delta^{net} = 2T\_DC$ (Time Data Cycle) (if we consider $T\_DC = 125\mu s$, $\delta^{net} = 250\mu s$), and $\sigma = 10$, then we obtain an horizon $h = 24$. The simulation result expressed in terms of performace loss, due to the network in the loop, is:

Case 1 ($\sigma = 10$, $\delta^{net} = 2$, $k^{cmp} = 0.5$, $h = 24$)

	area error	average radial rel. error	maximum radial rel. error
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PBC approach	0.0914	0.0914	0.1261

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Case 2 ($\sigma = 20$, $\delta^{net} = 5$, $k^{cmp} = 0.5$, $h = 50$)

	area error	average radial rel. error	maximum radial rel. error
Conventional control	1.1634	1.2868	0.0858
PBC approach	0.1159	0.1160	0.1518

Contribution and conclusions

The problem of model-based approach to control a nonlinear system based on its approximate discrete-time model is not new. In particular, we referred mainly to the following works: **Delay compensation in packet-switching networked controlled systems** (Chaillet and Bicchi), and **Exploiting packet size in uncertain nonlinear networked control systems** (Greco, Chaillet, Bicchi). In particular, these works consider a static controller for state feedback whereas here a dynamic controller is considered. Therefore, the main aim of my work has been to show the practicality and the applicability of the control approach even when considering a dynamic controller. In order to evaluate the performance of the proposed control strategy, the control algorithm has been implemented and tested on a industrial case study. The results obtained by means of simulations are very promising. In fact, they suggest the possibility of:

- exploiting the large size of packets and consequently lowering the sending packet-rate
- using the available bandwidth in a better way, while ensuring a certain quality of control
- lowering the requirements real-time of the communication, and therefore extending the control to the green phase of PROFINET

Future works:

- the proof of the stability of the control-loop by taking into account the network constraints, the dynamic controller, and the model uncertainty
- to design a non-linear observer well-suited for packet-switching network
- development of a demonstration with a real mechanical system